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C-130J Human Vibration

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ABSTRACT

Human exposure to whole-body vibration (WBV) has been associated with a variety of changes in health, comfort, and occupational functioning. In the C-130J Hercules aircraft, crews from both Australia and overseas have reported that the vibration in the cargo compartment of the aircraft exceeds previous levels and that it is both annoying and fatigue-promoting. This report examines the issue of human vibration in the C-130J, providing an overview of the characteristics of vibration and human exposure to vibration, as well as a review of studies that have measured the vibration levels in the C-130J. The likely consequences of exposure to vibration in the aircraft are discussed and recommendations for managing the issue are provided.

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Executive Summary

Since the introduction of the C-130J-30 (Hercules transport aircraft) into service with the RAAF, operational personnel have expressed concerns about the vibration levels being experienced in the cargo compartment of the aircraft, claiming that they exceed those experienced in previous models. DSTO was requested to analyse existing data and determine the possible effects, from both an occupational health and safety, and personnel performance perspective, of the vibration on passengers and crew members carried on the C-130J-30 aircraft.

The first three sections of this report provide general information about human exposure to vibration (discussion of the main characteristics of vibration; the effects of exposure to vibration on health, comfort, and performance; standards for human vibration exposure; and methods of reducing vibration levels). In the fourth section four studies of human vibration in the C-130J are reviewed. The main characteristics of the C-130J vibration environment are specified, including the High Vibration Zone (HVZ), and possible consequences of exposure to the C-130J vibration environment are discussed.

The following recommendations for managing human vibration issues in the C-130J are made in the final section of the report:

1. The vibration levels measured on the **flight deck** of the C-130J are unlikely to result in either short-term or long-term deleterious effects on the health and functioning of aircrew.
2. While the precise impact of 100 Hz vibrations on aircrew and passengers is uncertain, the magnitude of the vibration and the likely length of exposure mean that it is highly unlikely that significant and chronic **health effects** would be experienced. This conclusion holds for passengers with normal health. Until definitive advice/studies are produced to clear the HVZ of the aircraft of health risk to aeromedical evacuation patients, it is recommended that such passengers are not transported in the HVZ of the aircraft.
3. In the absence of scientific evidence that the vibration environment of the C-130J-30 has no significant impact on the physical and mental functioning required for military operations, that passengers who will be required to undertake high risk military operations immediately upon completion of the flight (e.g., airdrop and combat airland operations) should not be seated in the HVZ for prolonged periods.
4. On the assumption that the accommodation of passengers in the HVZ is necessary for optimising military objectives it is recommended that strategies to reduce the vibration transmitted to passengers seated in this zone be explored. These strategies range from reducing the level of blade pass frequency

vibration through optimisation of synchrophase angles, to the isolation of passenger seating through more effective mounting of the seats to the sidewall, to the use of seat cushions/padding. In all of these cases it would be necessary to measure vibration levels at the seat pan following the application of any of these strategies. A critical issue is determining an appropriate target level of vibration to achieve. As the flight deck vibration levels have been deemed acceptable, they could be considered an appropriate target.

5. It is recommended that laboratory or in situ studies be carried out to determine the effect of the C-130J vibration environment on human performance, the duration of any of these effects, and to validate the extent of the proposed HVZ.

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Robyn Hopcroft joined DSTO as a Human Factors Engineer after graduating with a Bachelor of Behavioural Science degree with Honours from La Trobe University, Australia, in 2001. Robyn has worked on a variety of projects including the development of training interventions to improve safety in F-111 operations and the investigation of the usefulness of multi-layer displays for tracking of multiple objects. Her current research interests include human-machine interfaces associated with unmanned aerial vehicles and the development of theories and methods for cognitive work analysis.

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Contents

Glossary

AFFTC	Air Force Flight Test Center
AFIERA	Air Force Institute for Environment, Safety and Occupational Health Risk Analysis
AFRL	Air Force Research Laboratory
ARWO	Aerial Weather Reconnaissance Officer
AS	Australian Standard
dB	decibels
DSO	dropsonde system operator
FDPB	fatigue-decreased proficiency boundary
HVZ	high vibration zone
Hz	hertz
ISO	International Organisation for Standardization
KIAS	knots in actual speed
MEDEVAC	Aeromedical Evacuation
NAL	National Acoustic Laboratories
RAAF	Royal Australian Air Force
RAF	Royal Air Force
r.m.s.	root-mean-square
SEAT	seat effective amplitude transmissibility
VDV	vibration dose value
VWF	vibration-induced white finger
WBV	whole body vibration

1. Introduction

The impact of vibration on the human body has various implications for the health, comfort, and occupational functioning of those who work in vibrating environments. One such environment is that of the C-130J-30 aircraft - the latest C-130 capability acquired by the RAAF. C-130J aircrews from both Australia and overseas have noted that the vibration levels in the aircraft seem to be quite high, and hence concerns have been raised regarding the effect this might have on crew and passengers. This report is concerned not only with provision of general information about human exposure to vibration, but also with human exposure to vibration in the C-130J in particular.

The aim of this introductory section is to provide a brief outline of the characteristics of vibration, and the different ways in which people may be exposed to it. Subsequent sections will provide details of the possible effects of vibration on the health and performance of exposed humans, and some information on limiting exposure to whole-body vibration (WBV), including a basic outline of seating dynamics and of the standards that can be used for assessing exposure to WBV. The findings of four investigations of human exposure to vibration in the C-130J will be summarised (from Australia, the UK, and the USA) followed by a discussion of the possible consequences of exposure to vibration in the C-130J, and how exposure to vibration in the C-130J may be reduced. Finally, recommendations regarding human exposure to vibration in the C-130J will be given.

1.1 Characteristics of Vibration

In examination of the impact of vibration upon the human body, there are several characteristics of the vibration that must be taken into account. Direction, rotation, frequency, magnitude, point of entry, and duration are all factors which play a part in determining how vibration is transmitted throughout the body, and hence, how the body changes as a result. Direction of vibration is expressed in terms of three linear axes. These axes of vibration are fore-and–aft (x axis), lateral (y axis), and vertical (z axis). On the human body, the x axis is mapped as being from the back-to-chest, the y axis is from the right-to-left side, and the z axis is from foot-to-head in the standing or recumbent individual, and buttocks-to-head in the seated individual (Griffin, 1990). There are also three rotational vectors that vibration will follow – roll, pitch, and yaw, which correspond to rotation about the x, y, and z axes respectively. Rotational vectors are not usually measured in investigations of occupational vibration (Griffin, 1990).

Frequency is usually expressed in cycles per second in hertz (Hz). Exposure to certain vibration frequencies may have profound effects on specific parts and systems of the body, particularly if the frequency of vibration corresponds to the resonant frequency of that body part or system. In such cases, vibration in that area is likely to be amplified and therefore may have more pronounced effects on that area as compared to other parts of the body. For vibrations transmitted in the z direction (e.g., for seated individuals where most vibration may be transmitted from a seat pan to the buttocks), resonance for the abdomen, including the soft organs and respiration occurs at approximately 4-8 Hz; spinal and upper

torso resonances occur at 10-12 Hz; head and neck resonance occurs at around 30 Hz; and, the eyeballs are resonant at 60-90 Hz (von Gierke, McCloskey, & Albery, 1991; Grandjean, 1988). With regard to transmission of vibration throughout the body, in general, the higher the frequency of the vibration, the faster the vibration is attenuated as it moves throughout the body.

The magnitude of vibration is usually expressed in terms of acceleration (a less problematic measure than displacement and velocity). Most standards require that acceleration is expressed in metres per second per second (m/s^2) although other units of measurement, such as 'g' ($1g = 9.80665\ m/s^2$) are also used in certain circumstances. The absolute threshold for perception of vertical vibration for frequencies between 1 and 100 Hz is approximately $0.01\ m/s^2$ (Griffin, 1990). Doubling of magnitude within this range will result in an approximate doubling of the sensation of discomfort. The International Organisation for Standardization (ISO), has provided the following guidelines relating magnitude to comfort for passengers on public transport:

$< 0.315\ m/s^2$	not uncomfortable
$0.315\text{-}0.63\ m/s^2$	a little uncomfortable
$0.5\text{-}1\ m/s^2$	fairly uncomfortable
$0.8\text{-}1.6\ m/s^2$	uncomfortable
$1.25\text{-}2.5\ m/s^2$	very uncomfortable
$>2\ m/s^2$	extremely uncomfortable

Obviously passengers' perception of comfort would also depend on their expectations (e.g., the activities they would expect to accomplish), as well as other characteristics of the vibration such as frequency and duration (ISO 2631/1, 1997). For example, some visual discomfort might be expected with exposure to frequencies between 60 and 90 Hz – the approximate range of resonance of the eyeballs. Average magnitude is usually expressed as a *root-mean-square* value (m/s^2 r.m.s.) when examining human vibration exposure.

It has been generally accepted that discomfort increases with exposure time (Kjellberg, 1990), although the exact relationship is not straightforward. A vibration dose value (VDV) can be calculated to give an estimate of total exposure, taking duration into account. The VDV gives an indication of the magnitude of a one second duration of vibration that is of equivalent severity to the measured vibration, and is expressed in $m/s^{1.75}$ or in radians per second to the power 1.75 ($rad/s^{1.75}$)(ISO 2631/1, 1997). Formulas for calculation of the VDV vary depending on the complexity of the vibration. While a few minutes of exposure to vibration is generally thought to cause only small physiological changes (such as slight hyperventilation), the causal link between long-term exposure and physiological change is unclear (Kjellberg, 1990; Sanders & McCormick, 1993).

While vibration is complicated enough just taking these few factors into account, a full understanding of its nature and how it will be transmitted through the human body also requires consideration of the fact that in most settings vibration will be random rather than sinusoidal, and there will be numerous different types of vibration occurring at the same time (i.e., of varying frequency, direction, and magnitude). Point of entry is a major influence on how vibration is transmitted through the body. For example, if standing,

vibration will enter through the feet, but if seated most vibration will enter via the ischial tuberosities (lower posterior hip bone). If seated and reclining against a head/back rest more vibration will enter at the head and shoulders. The transmission and subsequent effects of several different types of vibration all acting on the body at the same time cannot be determined by merely summing the impact of each individual frequency (Griffin, 1990; Kjellberg, 1990). While a Fourier spectrum may be used to show a breakdown of the constituent parts of an observed vibration, as of yet, there is no really satisfactory method for examining the impact of vibration with full consideration of the interactions between different components. So while we might associate a particular frequency with particular symptoms or a decrement in performance of a particular task, the true relationship of frequency to impact on the body is not clear-cut.

1.2 Types of Vibration Exposure

Human exposure and response to vibration has been broadly classified as *whole-body vibration (WBV)*, *local (segmental, hand-transmitted) vibration,* and *motion sickness.* Another type of exposure, which will not be discussed here, is *impact vibration*, which refers to exposure to a single impact or shock (e.g., hammering a nail).

Note that the distinction between whole-body vibration and other more localised forms of vibration is not precise. Both types of exposure will result in transmission of vibration throughout the whole body and whole-body exposure commonly has localised components (e.g., seated persons are often exposed to local vibration of the head, hands, and feet). Likewise, motion sickness and WBV are not easily distinguished, given that motion sickness may occur as a result of exposure to WBV.

1.2.1 Whole-body Vibration (WBV)

Whole-body exposure to vibration arises where the body is supported on a vibrating surface. In most cases this occurs when one is sitting on a vibrating seat, standing on a vibrating floor, or lying on a vibrating bed. Typically WBV is experienced in transport, and in the vicinity of some types of machinery, and it usually involves vibration frequencies ranging from 0.5 to 80 Hz (Griffin, 1990). WBV does not have one specific target organ, and has been associated with a variety of health problems (Kjellberg, 1990). These include backaches, gastrointestinal, reproductive system, visual and vestibular disorders (e.g., Aantaa, Virolainen, & Karskela, 1977; Bovenzi & Hulshof, 1999; Dupuis & Zerlett, 1986; Kittusamy & Buchholz, 2004; Seidel, 1993). There is also evidence of intervertebral disc problems and degeneration of spinal vertebrae (e.g., Beevis & Foreshaw, 1985; Sandover, 1985; Shwarze, Notbohm, Dupuis, & Hartung, 1998). The effects of WBV will be covered in more detail in section 2 of this report.

1.2.2 Local vibration

Local vibration and segmental vibration are terms that have been used to refer to exposure when vibration is transmitted from a vibrating surface to part of the body. Often this exposure is also referred to as hand-arm, or hand-transmitted vibration, as it most commonly occurs with the use of vibrating tools, which are often hand-held. Most tools

vibrate in the range of 8 to 1000 Hz (Griffin, 1990). Local vibration has been associated with circulatory disorders, bone and joint disorders, neurological disorders, muscle disorders and other general disorders (e.g., central nervous system) (Griffin, 1990).

The most prominent health problem associated with exposure to vibration by the use of hand tools is the vascular disorder most commonly known as *vibration-induced white finger* (VWF), which occurs due to damage of the small blood vessels of the fingers. This condition arises only after long-term prolonged exposure to hand-transmitted vibration (it can take 4-10 years before symptoms begin), and is characterised by blanching of fingertips (progressing to whole fingers), and reduced sensitivity, followed by a sudden return of blood (red flush) with intense pain. VWF usually occurs as a result of exposure to vibration between 25 and 250 Hz (however there is some evidence that higher frequencies might also cause vascular problems). An associated neurological condition – sometimes known as *vibratory neuropathy*, may appear prior to, and during the course of VWF blanching. This represents the sensory changes due to damage of unmyelinated nerve endings in the fingers, and can be responsible for the tingling or numbness of the fingers that occurs during an attack of blanching (Griffin, 1990; Wasserman, 1987). Bone and joint disorders (e.g., osteoarthritis, degeneration or deformity of bones of the hands, decalcification, cysts, and vacuoles) are associated most frequently with percussive vibration between approximately 10 and 50 Hz (Griffin, 1990; 1998b).

1.2.3 Motion Sickness

Motion sickness results from exposure to frequencies below 1 Hz, more particularly those below 0.5 Hz (Griffin, 1990). Symptoms are many and varied, but may include vomiting, nausea, sweating, spatial unease, drowsiness, and dizziness. While motion sickness is most common in children, and many fail to show signs of susceptibility in adulthood, it has been demonstrated that everyone may be made sick if the appropriate stimulus is used (Griffin, 1997). Symptoms are most frequently observed in moving vehicles but there are a number of other environments where motion sickness may be initiated (e.g., fairground devices, simulators, microfiche readers, swimming) (Griffin, 1997).

The frequency-dependent effects of vibration on humans are summarised in Figure 1.

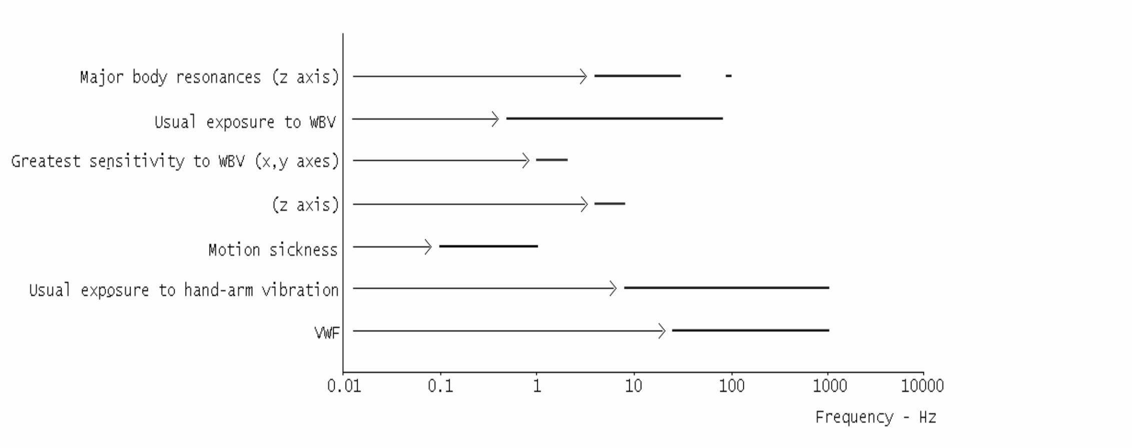

Figure 1 Frequency-dependent effects of vibration on humans.

2. An Overview of Effects of Exposure to Vibration

While a multitude of studies have been conducted to investigate the impact of vibration on humans, it is difficult to draw firm conclusions from them. In most cases many factors co-vary, making it difficult to determine the true cause/s of the various changes in health, comfort, and occupational functioning that have been observed. For example, the duties of participants in most occupational investigations (often epidemiological studies of truck drivers) mean that it is hard to separate the effects of vibration from those of sitting all day, and performing manual loading and unloading tasks. Intrinsic variables such as body posture, position, and orientation; body size, weight, level of fitness, and dynamic response of the body to vibration will influence how vibration is transmitted and therefore how it is perceived. The influence of a small change in posture can be large (and this influence is greater at higher frequencies), as minor changes in muscle tension and position can affect where vibration enters the body, and how vibration moves throughout the body. Poor posture at the head and lower back, for example, might result in increased transmission of vibration up the head and spine (Griffin, 1990). In general, increased body size is associated with reduced z-axis seat –to-head transmission of vibration for most frequencies between 1 and 100 Hz (Griffin, 1990). Transmission of vibration may also vary with age and gender. For example, susceptibility to motion sickness is higher for females, and usually decreases with age (for both males and females). With regard to comfort, females are more sensitive to certain frequencies of vibration than males (Griffin, 1990). Experience of vibration can result in habituation, and also better prepare the individual to respond (e.g., through changes in posture), thus reducing the impact of vibration. Experience, along with personality and attitude are also likely to influence expectations of vibration (how it will feel, how much it will interfere with activities etc.) that in turn will influence how it is perceived, and how the body changes in response to it. Thus, response to vibration exposure is highly individual, such that it is difficult to generalise very specific effects from person to person. Likewise, extrinsic variables, including the characteristics of the vibration, as well as other stressors such as noise and temperature, and seat dynamics, mean that generalisation from exposure in one environment to another is problematic. Seating dynamics will be discussed further in section 3.1.

Despite these difficulties in drawing firm conclusions from past studies on human vibration exposure, it is useful to gain a general notion of how people might be affected under certain conditions. Although thorough testing of individuals under the exact environmental conditions which are of interest is essential for a fuller understanding of vibration effects in context, it is pertinent here to give a general overview of some past research findings outlining various physiological, pathological and performance changes which have been associated with exposure to vibration. Given that the focus of this report will be on exposure to vibration in aircraft (in particular the C-130J), where WBV exposure is the main concern, changes associated with WBV will be of more interest than those related to local vibration.

2.1 Physiological and Pathological Changes

Vibration may cause changes to the body in a number of ways. For example, hyperventilation, which is caused by the passive movement of vibration through the abdominal wall, is basically a result the mechanical effects of vibration (i.e., exposure to vibration causes various internal organs to vibrate). An increase in heart rate is also observed at the beginning of exposure, but is believed to be a stress response (Kjellberg, 1990; Wasserman, 1987). Higher oxygen consumption is also associated with exposure to WBV. The level of influence such changes will have on functioning is dependent on the individual, and also on the task at hand. For example, Griffin (1990) suggests "moderate to high magnitudes of vertical vibration in the range from about 2 to 20 Hz produce a cardiovascular response similar to that normally occurring during moderate exercise" (p. 174). However, if the individual exposed to vibration is completing a very stressful task that results in a high stress response (i.e., high heart rate, oxygen consumption etc.), even a small cardiac change as a result of vibration exposure could potentially have large impact upon health, safety and performance.

Whilst various studies have reported small biochemical changes (blood count, endocrines, uric acid, enzyme levels, gastric secretions etc.) following exposure to vibration, generally they have not been significant, and levels observed were still within the normal physiological range (Dupuis & Zerlett, 1986). Such results suggest that in most cases of exposure to vibration these changes are unlikely to have an effect on functioning.

Disorders of the back (e.g., back pain, displacement of intervertebral discs, degeneration of spinal vertebrae, osteoarthritis) have commonly been associated with exposure to vibration. Severity and incidence is variable, and in some cases onset of mild to severe back pain can occur after only short periods of exposure to vibration (Reader, 1985). There is some disagreement as to the level of influence that other factors, particularly posture, may have on development of such problems, but most researchers acknowledge that posture is likely to be a large contributor to much of the back pain reported by those who work in vibrating environments (Kittusamy & Buchholz, 2004). For example, Beevis and Forshaw (1985) concluded that posture was likely to contribute to the back complaints of drivers of armoured personnel carriers in the military. However, a number of back pain reports varied with different vibration profiles (i.e., there were more reports for those who drove vehicles with higher levels of vibration), suggesting that posture was not the only contributing factor, and that vibration was also an influence. Reader (1985), and Braithwaite and Vyrnwy-Jones (1985) have conducted evaluations of new seats designed to improve lumbar support in military helicopters, and have found that reports of backaches have decreased following instalment of the seats. This suggests that posture has a large influence on the likelihood of experiencing back pain, however, changes in transmission of vibration that occurred with the new seats were not reported.

Despite numerous epidemiological studies as yet there is no reliable exposure-effect relationship for prediction of risks to the spine following exposure to vibration (Seidel, 1993). Sandover (1985) has suggested that occupational exposure to vibration could lead to earlier onset or increased incidence of back problems (i.e., degeneration of the lumbar spine). However, he noted that gaps in knowledge prevent researchers from presenting

any further conclusions. More recently, Schwarze et al. (1998) conducted a longitudinal field study of 388 drivers of different vehicles and found that vibration is a health hazard to the lumbar spine. The risk of developing "lumbar syndromes" (i.e., lower back pain) was found to increase with increasing vibration dose (taking into account both duration and magnitude). Such work gives some guidance as to the exposure-effect relationship for some specific back problems, but an overall picture of the effects of vibration on disorders of the back requires further investigation.

Other conditions associated with vibration include abdominal pain, digestive disorders, urinary frequency, peripheral vein damage, female reproductive system damage, prostatitis and haemorrhoids to name but a few. Balance and visual disorders, headaches and sleeplessness have also been observed (Griffin, 1990). Most of these conditions have been observed following long-term exposure to vibration for long durations. Some, such as sleeplessness, are most frequently associated with exposure to hand-arm vibration (Griffin, 1990). Again, further research is required to determine whether vibration is actually the primary cause (Griffin, 1998b). Unfortunately, there is little information on the likelihood of developing these types of disorders as a result of less frequent exposures of shorter durations. Most research tends to examine the effects of a few minutes or seconds of exposure (i.e., laboratory studies or sudden impacts), or several years of exposure to vibration for long durations (i.e., epidemiological studies). While the likelihood of development of most disorders tends to increase with increased magnitude and duration of exposure to vibration, the impact of vibration on those exposed for durations that fall in between the extreme short-term and long-term is not well known.

Several conditions have been associated with exposure to vibration within specific ranges of frequencies. The influence of frequency on the body is accounted for in a very general sense by *frequency weightings*, where frequencies of greater influence (i.e., requiring lower magnitudes to have an effect) are given higher weighting values. Human sensitivity to WBV is highest around 4-8 Hz in the z direction, and 1-2 Hz in the x and y directions (Bonney, 1995). At very low frequencies (i.e., less than 2 Hz) of vertical vibration, most body parts move up and down in unison. The sensation tends to be one of being pushed up and then floating down. Activities involving use of the hands may be affected by disturbances to free movement of the hands. Below 1 Hz (usually below 0.5Hz) motion sickness may occur. Low frequency horizontal vibration tends to cause the body to sway (although this may be resisted through muscular action or seating support) and it becomes difficult to stabilize the upper body, and quite uncomfortable. With increasing frequency, horizontal vibration is less well transmitted to the upper body (Griffin, 1990).

Pains in the chest and abdomen have been observed with exposure to vibration ranging from 4 to 10 Hz, while backaches commonly occur at 8-12 Hz. Headaches, eyestrain, and irritations in the intestines and bladder occur between 10-20 Hz (Grandjean, 1988). With regard to high magnitude, high frequency vibration, respiratory problems and giddiness have been observed at 60 and 73 Hz, and mild nausea, giddiness, subcostal discomfort, cutaneous flushing and tingling have been observed at around 100 Hz (Mohr, Cole, Guild, & von Gierke, 1965), but it should be noted that these vibration levels were high magnitude, induced by high intensity noise.

Although substantial fatigue was reported following exposure to high magnitude vibration (in excess of 10 m/s^2) for durations of at least 2 minutes (Mohr, Cole, Guild & von Gierke, 1965; Smith, 2002a), there is little other information concerned with the association between fatigue and vibration exposure (Griffin, 1998b).

2.2 Performance Effects

Vibration has been observed to have an impact on performance of various tasks, involving vision, motor activity, and information processing. Performance is worse when there are various frequencies of vibration occurring at the same time, and better when vibration is random (although more uncomfortable) (Wasserman, 1987). This effect may be due to the direct effects of vibration on input and output processes (e.g., vision, hand movements), or indirect effects, through other changes such as motivation, mood, and arousal. For example, Abbate et al. (2004), found that exposure to WBV is associated with alterations of emotional states. Fatigue-inertia, depression-dejection and tension-anxiety scales of the Profile of Mood States were elevated for those exposed to occupational WBV over a long period, and these effects were correlated with length of exposure. Wilkinson and Gray (1974) found that vibration can have an arousing effect on tasks completed under unmotivating conditions (i.e., when no feedback is provided), as evidenced by improved performance at the task. Poulton (1978), reported that exposure to vibration at frequencies between 3.5 and 6 Hz can have an arousing effect, resulting in improved performance at boring vigilance tasks. This alertness is believed to be due to tensing of trunk muscles to attenuate shoulder vibration. Frequencies outside this range require relaxation of the trunk muscles to attenuate shoulder vibration, and hence, may decrease arousal (and possibly performance too). In cases where vibration results in arousal, and better performance of particular tasks, it is also important to consider that this may occur at the expense of performance on other tasks, and result in earlier fatigue. It has also been noted that different types of vibration may lead to use of different strategies (for example a task may be completed with fewer errors, but at a slower rate) (Griffin, 1990).

2.2.1 Vision

The effects of vibration on vision depend on the extent to which the vibration is transmitted to the eye. Below frequencies of about 10 Hz, the 'vestibulo-ocular reflex' will compensate for pitch motions of the head, thus maintaining the line of site (Griffin, 1998b). Such head movements will have little impact on vision, unless information is presented on a head-mounted display. Visual performance is most impaired in the range of 10-25 Hz (Sanders & McCormick, 1993). Translational head movements may cause difficulty with viewing of displays in close proximity, while viewing something in the distance will not be affected. At low frequencies, when both the observer and the display are vibrating together, vision is better than when only the observer, or only the display is vibrating. The threshold for visual detection that an object is vibrating is very low for low frequencies and high for high frequencies. Above this threshold there will be perceptible blur due to the movement of images over the retina (Griffin, 1998b).

It has also been shown that exposure to vibration (x and y axes) will affect reading speed and accuracy (Griffin & Hayward, 1994). In particular, reading speed is slowest at 4 Hz in

the range of 0.5-10 Hz that was tested. In the x and y axes reading was found to be worst at 4 Hz at a magnitude of 1.25 m/s^2 r.m.s. where speed was 71% and 78% of that observed under static conditions for the two axes respectively. Obviously such decrements in performance may be largely due to visual problems (i.e., blurring of print), however, there has been no comment as to the extent to which changes in higher cognitive processes might be responsible.

2.2.2 Motor Performance

Completion of tracking tasks has been used in various studies as an index of motor performance. It has been found that vibration between 4 and 20 Hz (at accelerations exceeding 0.20g) has a detrimental effect on such activity, and that there is still an effect up to 30 minutes after exposure to vibration has ceased (Hornick, 1973; Sanders & McCormick, 1993). It has been noted that vertical vibration usually results in the most errors and that low frequency vertical vibration between 0.20g and 0.80g can result in up to 40% more error than occurs when tracking under static conditions (Hornick, 1973). Exposure time does not appear to affect performance up until around 3 hours of exposure, such that a longer exposure to vibration does not result in a higher error rate. (Hornick, 1973; Sanders & McCormick, 1993).

There is evidence that vibration will result in suppression of reflex responses, and that this will continue after vibration has ceased (e.g., Martin, Roll, & Gauthier, 1984; Roll, Martin, Gauthier, & Mussa Ivaldi, 1980). The possibility that vibration may cause muscle fatigue has also been investigated, through measurement of electromyographic activity (Griffin, 1990). While there is limited evidence suggesting that this may be the case, more research would be necessary before any conclusions could be made regarding this matter. Pope, Wilder, and Donnermeyer (1985) examined electromyographic activity in the same vibrational environment as that experienced by helicopter pilots. They found that muscle fatigue was primarily due to the effect of posture rather than the vibrational environment.

2.2.3 Information Processing

The impact of vibration on higher cognitive processes has received little attention. The literature that does exist in this area suggests that while such processes may be highly resistant to degradation by vibration, there may still be some decrements in short–term memory and learning processes. Sherwood and Griffin (1990) found that reaction time and errors that occurred during performance of short-term memory tasks were higher during exposure to vibration at 16 Hz. The vibration parameters used in their experiment were selected to approximate conditions of some rotary-wing aircraft. The task was visual and required participants to observe a set of 2, 4, or 6 letters, and shortly thereafter a probe letter was presented, and participants were asked to identify whether the probe was a member of the original set of letters. Participants acted as their own controls, completing the tasks during exposure to vibration (at magnitudes of 1.0, 1.6, and 2.5 m/s^2 r.m.s.) and without vibration. Errors were particularly high at a magnitude of 1.0 m/s^2 r.m.s. (25% increase over static conditions) as were response times (5% increase over static conditions). These error rates and reaction times were also higher than those that occurred during vibration at 1.6 and 2.5 m/s^2 r.m.s. This led the researchers to suggest that there may be

compensatory processes that minimise effects of vibration when it reaches a certain magnitude.

Sherwood and Griffin (1992) conducted a study where they found that associative learning was impaired during exposure to 16 Hz WBV at a magnitude of 2.0 m $/s^2$ r.m.s. Participants were required to learn the team membership of a group of imaginary men (16 men belonged to Team A and 16 to Team B). Their names were then presented randomly to the participants and as each name appeared they were required indicate to which team the man belonged. Feedback was given on whether the response was “WRONG” or “CORRECT”. This procedure was repeated eight times, with the names presented randomly for each trial. A week later participants returned to complete a second session of five trials of the same task. Participants belonged to one of four groups depending on their exposure to vibration for the two sessions: static session 1, static session 2; static then vibrated; vibrated then vibrated; and, vibrated then static. It was found that performance of the task was worst when participants were exposed to vibration in either or both sessions, with a 10% to 15% reduction in learning/memory. It was also found that there were no context-dependent effects on learning. That is, participants learnt at a similar rate for session 1 and 2 even if they were learning in a different environment in the second session (i.e. session 1: static, session 2: vibrated, and vice versa). This finding has implications for aviation where aircrew often learn in a static environment, and need to recall that information whilst in a vibrating aircraft. It was apparent from the experiments that vibration was most likely impacting upon the learning process, rather than the process of recall, suggesting that the impairment was due to a disruption in the information input processes. Such effects on information processing would be more critical on the flight deck of an aircraft, where information processing underlies mission critical decisions. The effects may be small when translated to an operationally relevant domain but they could be significant under high workload, high stress conditions (for example, in a threat environment or a high traffic environment where it may be necessary to process and remember a lot of information with a lot of distracting sources of information around). The impact is likely to be less of an issue in the cargo/passenger compartment of an aircraft unless mission critical information needs to be conveyed and remembered by those in the cargo compartment.

3. Limiting the effects of WBV

Concern about the potential for harm as a result of exposure to WBV raises the issue of how to prevent, or at least limit such harm. The two most obvious courses of action are to either reduce the exposure time, or to reduce the magnitude of the vibration (particularly the most damaging frequencies). While reducing the exposure time would be desirable, in many cases it is not possible to change the time required to complete duties in the vibrating environment. However, through modification of the environment, transmission of vibration throughout the human body may be greatly reduced (Bonney, 1995). Modifications may include adaptations to seat design and flooring, and improvement of vehicle suspension. In order to reduce effects on performance, further adaptations may be made to visual displays (e.g., larger characters and collimation of displays may help in some circumstances) (Griffin, 1990). Also, motor performance at tracking tasks is highly

dependent on both displays and controls such that correct positioning of the controller will reduce error. Hornick (1973), found that use of a side-stick with arm support reduced vibration-induced error by 50% as compared to use of a centre-mounted joystick.

3.1 Seating Dynamics

Given that many instances of exposure to vibration occur when individuals are seated, it is important to consider how the properties of the seat might influence the transmission of vibration throughout the body. A well-designed seat can help to limit exposure to WBV, and therefore reduce the risk of developing some of the problems that have been associated with such exposure. Features of the seat, such as the general shape, rigidity, or the presence of a backrest or lap belt can make large differences to the way that vibration will move throughout the body, and the resonances of the different body parts (von Gierke et al, 1991). For example, at low frequencies a backrest can help to stabilize the upper body and reduce the effects of motion. In contrast, at high frequencies, a backrest is the major cause of transmission to the upper body, and can greatly increase the effects of fore-and-aft vibration (Griffin, 1990). Hence, one of the major difficulties with seat design is the problem of multi-frequency vibration environments, particularly where a mixture of very low, and very high frequencies are exhibited.

The material of which the seat is composed is also an important determinant of how much vibration will reach the body. Selection of appropriate materials for the manufacture of seats can greatly reduce vibration exposure. Floors may also be lined, given that vibration is also usually transmitted through the feet when sitting. A useful indication of the effectiveness of a seat in isolating vibration, may be obtained through calculation of the 'seat effective amplitude transmissibility' (SEAT) (Griffin, 1990). This value is obtained through comparison of the severity of vibration at the seat to the severity of vibration on the floor below:

$$SEAT(\%) = \frac{Ride\ \ comfort\ \ on\ \ seat}{Ride\ \ comfort\ \ on\ \ floor} \times 100$$

A SEAT value in excess of 100% indicates that the vibration is actually worse at the seat than at the floor, whereas a value below 100% suggests that the seat may provide some useful protection against the effects of vibration. Thus, the design of appropriate seats for a vibrating environment entails finding out what type of structure, taking into account other concerns (functional, financial etc.), will yield the lowest SEAT value. Table 1 gives some examples of SEAT values for various types of seat cushions on passenger railway seats. High SEAT values are common for railway carriage seats as they do not provide any protection from the low frequency vibration that usually occurs inside trains. In contrast, common car SEAT values range from 60-80%, indicating that they provide useful attenuation of vibration.

Table 1 *SEAT values for various passenger railway seat cushions (data from Corbridge, Griffin, and Harborough, 1989).*

Cushion Type	SEAT (%)
30mm foam	102
60 mm foam	109
Rubberised hair	124
Foam cushion	127
Spring case A	141
Spring cushion	140

3.2 Standards for appropriate exposure to WBV

Given the concerns relating to the comfort, working efficiency, and health and safety of those exposed to vibration, attempts have been made to provide some standard to act as a guide for appropriate exposure to vibration. The International Organization for Standardization (ISO) has set guidelines for assessing WBV, motion sickness and hand-arm vibration, and many countries have developed similar standards. The Australian Standards for exposure to WBV (AS 2670.1 – 1990) were based on ISO standard 2631/1-1985. With regard to WBV, ISO 2631/1-1985 provides a 'reduced comfort boundary', fatigue-decreased proficiency boundary' (FDPB), and the 'exposure limit'. These boundaries (illustrated in Figure 2.) cover preservation of comfort, working efficiency, and health and safety respectively.

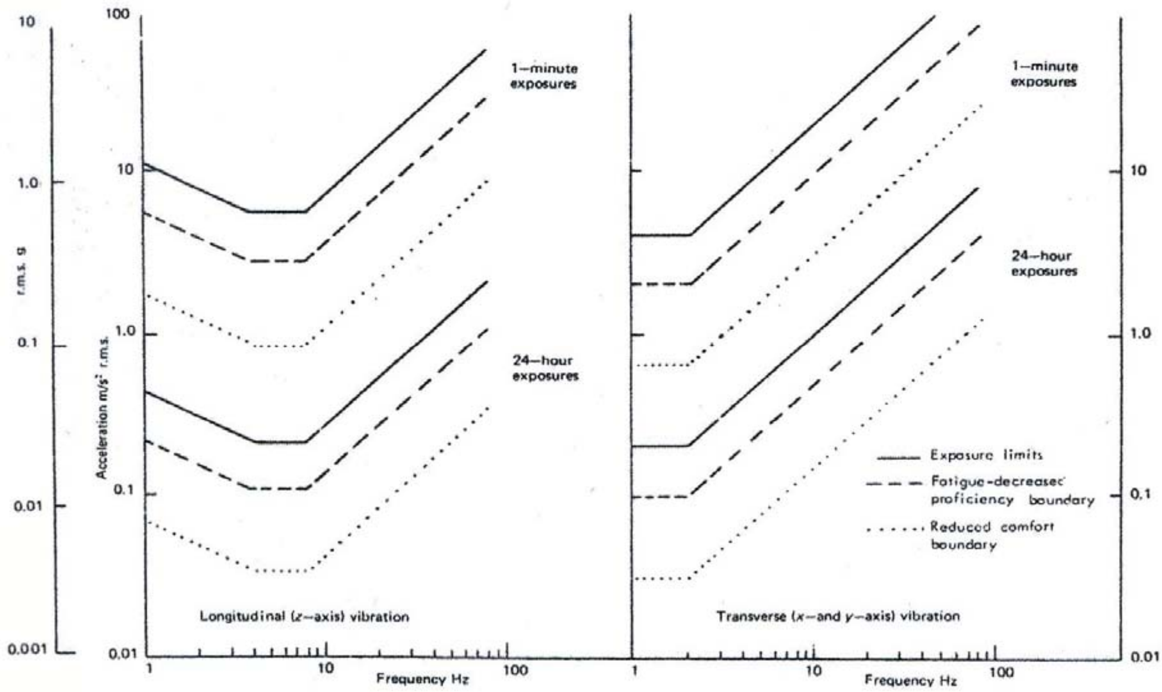

Figure 2 *Boundaries set out in ISO 2631/1-1985 for human exposure to mechanical vibration for 1 minute and 24 hours.*

Exceeding the FDPB for exposure to vibration is believed to compromise working efficiency for a variety of tasks, particularly those with time-dependent effects. The reduced comfort boundary, is calculated by dividing the FDPB by 3.15 (i.e., a reduction of 10 dB), and specifies the limit above which, discomfort due to vibration is likely to occur. It was developed using the results of studies of comfort in transport industries and is concerned with difficulties in carrying out activities such as eating, reading, and writing (Griffin, 1990; ISO 2631/1, 1985). The exposure limit is double the FDPB (i.e., an increase of 6 dB) and under normal circumstances should not be exceeded due to the risk this would pose for health. It is set at approximately half the threshold of pain, and it is recommended that the boundary not be exceeded without special justification (although examples of such justification are not given). Limits are expressed in terms of acceleration, frequency and exposure time. Frequency weightings are used to reflect the level of influence a frequency has on the body. For example, as shown in Figure 2, there is a dip in the boundary contour between 4 and 8 Hz as the body is most sensitive to these frequencies. Frequencies from 1 to 80Hz are covered by the boundaries for WBV exposure.

While these ISO guidelines for exposure to vibration are useful for reporting results, there have been various criticisms directed toward them, calling into question the utility of the boundaries as a true guideline for preservation of the comfort, working efficiency and health of those exposed to vibration (Sanders and McCormick, 1993). To summarise these criticisms, it has been said that (1) the boundaries appear to be too simplistic; and, (2) they are based upon insufficient evidence. For example, it has been noted the boundaries for comfort, working efficiency, and health are all the same shape although this is not likely to be the case in reality. Some suggest that the comfort boundaries may underestimate the impact of high frequencies and overestimate the impact of low frequencies (Corbridge & Griffin, 1986). It is also implied that combinations of single axis vibration are additive (despite evidence to the contrary), and the relationship of duration of exposure to health, comfort, and working efficiency is still uncertain, yet the boundaries are based on a complex duration-magnitude relationship. Finally, variability in response of the population isn't taken into account (Sanders & McCormick, 1993).

In order to address those criticisms directed specifically toward the scientific basis of the boundaries outlined in ISO 2631/1-1985, a newer version of ISO 2631/1 (1997) has been developed and adopted as the Australian Standard (AS 2670.1-2001). This standard relies on other methods for assessing the impact of vibration on health, comfort, perception, and motion sickness, abandoning the time-dependent boundaries (Griffin, 1998a). With regard to health, the standard uses a "caution zone" to classify exposure to vibration. Two equations can be used to calculate the caution zone as opinions on where the zone lies differ. For short exposure durations (under an hour) there is more uncertainty as to the likely health effects of vibration, whilst there is more agreement on the likely impact of longer exposure durations, such that the two caution zones are identical in the 4 to 8 hour exposure range. If exposure falls in the area above the caution zone there is likely to be a health risk. Inside the zone there is a potential health risk, whilst below the zone, there is no clear understanding of health effects. Figure 3 illustrates the caution zones as set out in ISO 2631/1-1997. Guidelines for the impact of vibration on comfort and the perception of vibration are also given (see section 1.1), and motion sickness dose values are used to

calculate the likelihood of vomiting due to motion sickness. Note that revision and amendments of the standard have occurred in an effort to reach a compromise between differing opinions within the scientific community. However, Griffin (1998a) suggests that ISO 2631 (1997) reflects "muddle and absence of agreement" rather than an identification of areas of consensus based on scientific evidence.

Another aspect of the ISO 2631 that can be problematic in assessment of certain instances of vibration exposures is that it only covers vibration of frequencies of up to 80 Hz for WBV. While most WBV exposure may occur for frequencies below 80 Hz, there are still instances where people will inevitably be exposed to higher frequencies (in fact subsequent sections dealing with vibration in the C-130J discuss the exposure of crew and passengers to 100 Hz vibration). The standards do not cover vibrations at frequencies above 80 Hz as they "…increasingly produce sensations and effects which are highly dependent upon local factors such as the precise direction, site and area of application of the vibration to the body and the presence of damping materials (for example, clothing or footwear) which may control the vibratory response of the skin and superficial layers of the body" (ISO 2631/1-1985). Hence, it not possible to merely extrapolate the current boundaries to find values for limits of exposure for higher frequencies. While standards for exposure to hand-transmitted vibration cover higher frequencies (80-1000Hz), they are based on the vibration entering the body through contact with the hand. It would not be wise to make the assumption that exposure to WBV above 80 Hz might be covered by the standards for hand-transmission.

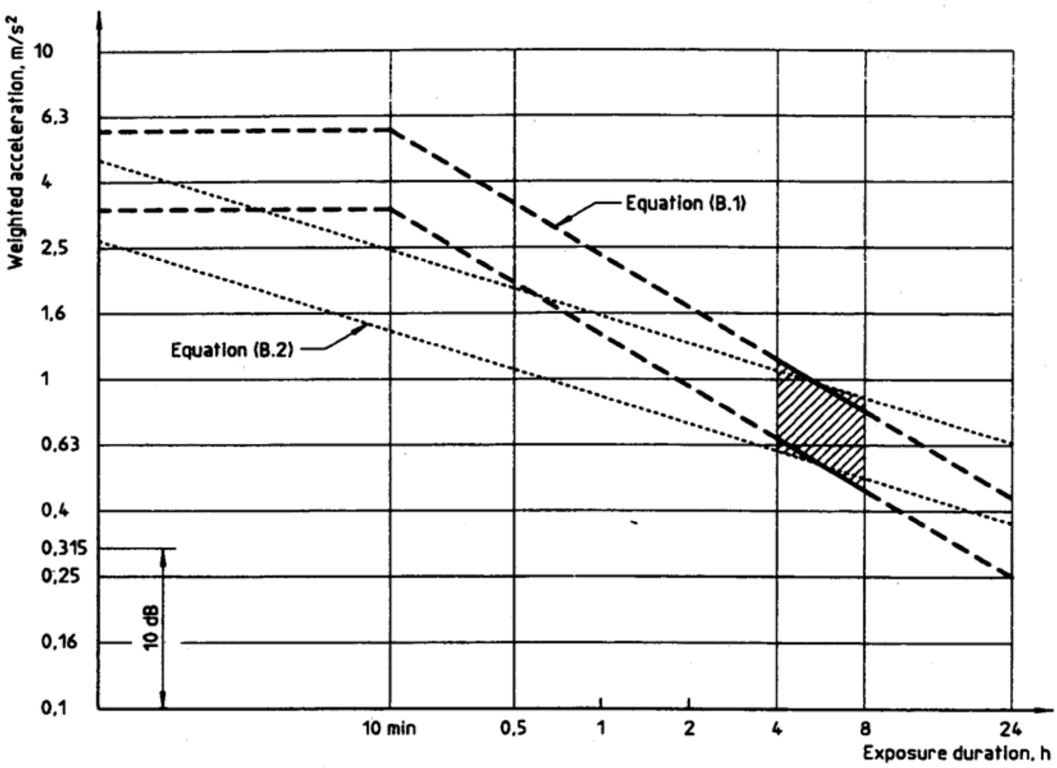

Figure 3 Health guidance caution zone from ISO 2631/1 (1997).

More recently, the European Union has reached agreement on a new directive dealing with vibration. The Human Vibration Directive 2002/44/EC is being phased-in over the next five years in participating countries. It provides an exposure limit that must not be exceeded, and action values, which indicate when protective procedures should be introduced for both hand-arm vibration and WBV. For hand-arm vibration the daily exposure limit (for an eight hour period) is $5 m/s^2$, and the daily exposure action value is $2.5\ m/s^2$. For WBV the daily exposure limit is $1.15\ m/s^2$(or at the choice of the Member state concerned, a VDV of $21\ m/s^{1.75}$), and the daily exposure action value is $0.5\ m/s^2$ (or at the choice of the Member State concerned, a VDV of $9.1\ m/s^{1.75}$). The possibility of exemptions in the case of air and sea transport is granted as "given the current state of the art it is not possible to comply in all circumstances with the exposure limit for whole-body vibration". The European directive also includes the provision that Member states ensure that the health of workers is monitored to prevent and diagnose rapidly, any problems that might be associated with the vibration.

Although the directive does not specify the frequency ranges that it covers, some of the calculations made are based on the most recent ISO standards, so presumably the same frequency ranges are covered (i.e., 1-80Hz for WBV). The directive is expected to result in many companies being forced to make changes in the workplace to reduce workers' exposure to vibration.

4. Vibration in the C-130J

Concerns about crew and passenger exposure to vibration in the C-130J have arisen following the reports of operational personnel that the vibration they were exposed to during flight appeared to exceed that experienced in earlier Hercules models, was annoying, and fatigue–promoting, and that they felt buzzing or tingling sensations (Smith, 2002b). Vibration was noted as being particularly prominent in the cargo compartment in the vicinity of the propeller plane. Such comments prompted research aimed at determining the characteristics of the vibration environment in the C-130J. To date there have been four studies that have measured whole body vibration levels in the C-130J.

4.1 C-130J Vibration Studies

AFIERA Study

The Air Force Institute for Environment, Safety and Occupational Health Risk Analysis (AFIERA, 2000) carried out the first study on a WC-130J to quantify perceived vibration exposure issues. Vibration levels were measured at the dropsonde system operator (DSO) station, located in the front of the cargo compartment, just forward of the propeller plane. Six main flight profiles were flown: Straight and Level, and Turning, 9000′, 180 Knots in actual speed (KIAS); sideslip; and three stall profiles – clean, 50% flap and 100% flap. The main feature of the vibration data was the presence of peaks in the 16 Hz third octave frequency band for all axes but in particular, the vertical (z) axis, and when the aircraft was at higher speeds (see Table 2). This frequency band corresponds to the 17 Hz propeller shaft speed of the engines. High levels were also found in the 4-5 Hz range. Levels in the

16 Hz frequency band (in the vertical, z-axis) exceeded the 8-hr fatigue-decreased proficiency boundaries, and in some cases the exposure limit, specified in ISO 2631.1:1985. These levels would fall above the caution zone in the ISO 2631.1:1997 standard, indicating that health risks would be likely.

AFFTC/AFIERA/AFRL Study

A second study (George, 2001; Smith, 2002b), involving the Air Force Flight Test Center (AFFTC), AFIERA, the Air Force Research Laboratory (AFRL), and Lockheed Martin, aimed to characterise the C-130J vibration environment as a function of aircraft configuration, status of propeller balancing, and flight regime (airspeed: 140, 180, 220 KIAS and Maximum Continuous Power, and altitude, from 4000′ up to 34000′). The AFIERA study had only reported frequencies inside the 1-80 Hz range, for a limited range of flight regimes. The data collected from this study would provide a more complete picture of the C-130J vibration environment.

Human vibration measurements were made at the Aerial Weather Reconnaissance Officer (ARWO) and DSO stations of a WC-130J; outer port and starboard passenger seats, and centreline passenger seats, in line with the propeller plane, in a "slick" C-130J (where the DSO and ARWO stations had been removed); and co-pilot and crew bunk stations. Peak acceleration was found in the 16 Hz and 100 Hz frequency bands, corresponding to the 17Hz rotor speed and 102 Hz Blade pass frequency. The 16 Hz peaks were nowhere near those obtained in the original AFIERA study (see Table 2), particularly in the z-axis. The vibration levels measured were below the health caution guidance zones for daily exposure. In a couple of instances the 16 Hz vibration in the z-axis exceeded 8 hour reduced comfort boundary, but only under conditions where the props were not balanced. Propeller balancing led to reductions in 16 Hz vibration levels for all axes in the WC-130J (this condition was not assessed in the "slick" C-130J).

Peaks within the 100 Hz 3rd-octave band were obtained across all conditions, although it was in the "slick" C-130J that significant levels were observed (see Table 3). These peaks occurred in the x (fore-and-aft) axis at the seat pan for outer port and starboard passenger seats in line with the propeller plane. High vibration levels were not observed at the seat pan of the centreline seats, however there was significant z (vertical) axis vibration at the seat base.

NAL/RAAF Study

The third study was carried out by the National Acoustic Laboratories in conjunction with RAAF Air Lift Group personnel (Cook & Jarvis, 2002). Three aircraft were tested, two C-130J-30 (one using dynamic propeller balancing) and one C-130H. One flight test was conducted on each aircraft, with the vibration measurements being conducted during the cruise phase of flight (at 25000′, 230 KIAS for the J and 200 KIAS for the H). This provided the first human vibration assessment of the "stretched" version of the J, and a comparison with an H model to determine more precisely what underlies the subjective assessment of the J as having a more uncomfortable vibration environment. In addition, the WBV experienced at a number of seat locations throughout the cargo compartment was assessed

to determine the extent of any problem areas. Vibration levels were measured at 16 seats in the first J; 12 in the second J; and 20 in the H. The majority of the seats assessed were in the vicinity of the propeller plane, including outer port and starboard seats and centreline seats. For comparison, the vibration levels experienced at seats at the front and rear of the cargo compartment were also measured.

The NAL/RAAF C-130J-30 findings were similar to those obtained with the “slick” C-130J in the AFFTC/AFIERA/AFRL study. Peaks were obtained in the 16 Hz and 100 Hz frequency bands. The 16 Hz levels were low for both C-130J-30 aircraft, although the levels were lower for the second aircraft that had its propellers dynamically balanced (see Table 2). High levels of x-axis vibration were obtained in the 100 Hz frequency band for outer port and starboard passenger seats in the propeller plane (see Table 3). As you move forward and aft of the propeller plane, vibration levels diminish, although the levels are still significant six seats either side of this plane. The level of vibration at the centreline passenger seats was considerably lower.

The vibrations levels measured in the C-130H were characterised by peaks in the 16 Hz and 68 Hz bands, corresponding to engine rotor speed and the blade pass frequency of the 4-bladed propellers. The 16 Hz levels were low and comparable to those measured on the C-130J and C-130J-30 aircraft (see Table 2). Higher levels of vibration were obtained in the 68 Hz band for seats in the propeller plane, particularly in the x-axis (see Table 3). These did not exceed the 8-hour fatigue-decreased proficiency boundary, but often exceeded the 8-hour reduced comfort boundary in the x and z-axes. The levels were below the health caution guidance zones for daily exposure. Noise levels recorded in the vicinity of the propeller plane were found to be 3 to 5 dB higher in the C-130J-30 than in the C-130H.

QinetiQ/RAF Study

A fourth study was carried out by QinetiQ in conjunction with RAF Air Lift Group personnel (Leeks, Corry, & James, 2002). While extensive measurements were made for many locations in both the standard (CMK5) and stretched (CMK4) versions of the C-130J, these were made on the floor, rather than at the seat pan. Seat pan acceleration data are required for assessing exposure in accordance with the international standards as the measurement represents the vibration entering the occupant and takes into account any damping (or increase) of the motion associated with the seating system.

Table 2 Selected C-130J whole body vibration results for 16 hz 3rd octave frequency band.

Study	Measurement Conditions	Vibration (ms^{-2} rms)
AFIERA	*WC130J DSO Station*	
	Straight & Level, 9000’, 180 KIAS	0.14 (x) 0.05 (y) 9.44 (z)
	WC130J DSO Station	
WC130J	Turning, 9000’, 160 KIAS	0.20 (x) 0.07 (y) 8.51 (z)
	WC130J DSO Station	
	Sideslip	0.14 (x) 0.09 (y) 4.95 (z)
	Stall 50% Flaps	0.22 (x) 0.10 (y) 6.38 (z)
	Stall 100% Flaps	0.11 (x) 0.07 (y) 4.73 (z)
AFFTC/AFIERA/AFRL	*WC130J DSO Station*	
	4000’, 220 KIAS, Props Balanced	0.02 (x) 0.04 (y) 0.02 (z)
	10000’, 180 KIAS, Props Balanced	0.05 (x) 0.01 (y) 0.02 (z)
	24000’, 220 KIAS, Props Balanced	0.02 (x) 0.03 (y) 0.05 (z)
WC130J	*WC130J ARWO Station*	
	4000’, 220 KIAS, Props Balanced	0.03 (x) 0.08 (y) 0.06 (z)
	10000’, 180 KIAS, Props Balanced	0.03 (x) 0.14 (y) 0.07 (z)
	24000’, 220 KIAS, Props Balanced	0.02 (x) 0.06 (y) 0.03 (z)
	WC130J ARWO Station	
	4000’, 220 KIAS, Props As-Is	0.17 (x) 0.51 (y) 0.33 (z)
	10000’, 180 KIAS, Props As-Is	0.16 (x) 0.39 (y) 0.27 (z)
	24000’, 220 KIAS, Props As-Is	0.10 (x) 0.22 (y) 0.18 (z)
	C130J Left Seat	
	24000’, 220 KIAS, Props Balanced	0.09 (x) 0.01 (y) 0.05 (z)
C130J	*C130J Right Seat*	
	24000’, 220 KIAS, Props Balanced	0.08 (x) 0.02 (y) 0.05 (z)
	C130J Centre Seat	
	24000’, 220 KIAS, Props Balanced	0.08 (x) 0.01 (y) 0.06 (z)
NAL/RAAF	*Left Seat Propeller Plane*	
* Includes comparable	C130J 25000’, 230 KIAS, Balanced	0.05 (x) 0.02 (y) 0.03 (z)
C130H results for 16 Hz	C130J 25000’, 230 KIAS, Props As-Is	0.20 (x) 0.03 (y) 0.20 (z)
band	*C130H 25000’, 200 KIAS	0.04 (x) 0.01 (y) 0.02 (z)
	Right Seat Propeller Plane	
	C130J 25000’, 230 KIAS, Balanced	0.05 (x) 0.01 (y) 0.01 (z)
	C130J 25000’, 230 KIAS, Props As-Is	0.15 (x) 0.04 (y) 0.08 (z)
	*C130H 25000’, 200 KIAS	0.04 (x) 0.01 (y) 0.03 (z)
	Centre Seat Propeller Plane	
	C130J 25000’, 230 KIAS, Balanced	0.04 (x) 0.01 (y) 0.01 (z)
	C130J 25000’, 230 KIAS, Props As-Is	0.10 (x) 0.04 (y) 0.03 (z)
	*C130H 25000’, 200 KIAS	0.03 (x) 0.02 (y) 0.01 (z)

Table 3 Selected C-130J whole body vibration results for 100 Hz 3rd octave frequency band (with comparison results for the C-130H for the 68 Hz 3rd octave frequency band).

Study	Measurement Conditions	Vibration (ms^{-2} rms)
AFFTC/AFIERA/AFRL	*WC130J ARWO Station*	
	4000’, 220 KIAS, Props Balanced	0.10 (x) 0.10 (y) 0.10 (z)
WC130J	10000’, 180 KIAS, Props Balanced	0.20 (x) 0.10 (y) 0.10 (z)
	24000’, 220 KIAS, Props Balanced	0.80 (x) 0.80 (y) 0.30 (z)
	WC130J DSO Station	
	4000’, 220 KIAS, Props Balanced	0.70 (x) 0.20 (y) 0.10 (z)
	10000’, 180 KIAS, Props Balanced	0.10 (x) 0.50 (y) 0.20 (z)
	24000’, 220 KIAS, Props Balanced	0.60 (x) 0.30 (y) 0.10 (z)
	C130J Left Seat	
	24000’, 220 KIAS, Props Balanced	7.50 (x) 2.50 (y) 1.00 (z)
	Seat base	1.50 (x) 0.50 (y) 4.80 (z)
C130J	*C130J Right Seat*	
	24000’, 220 KIAS, Props Balanced	2.00 (x) 1.00 (y) 0.50 (z)
	C130J Centre Seat	
	24000’, 220 KIAS, Props Balanced	0.50 (x) 0.30 (y) 0.30 (z)
	Seat base	2.50 (x) 3.00 (y) 10.5 (z)
NAL/RAAF	*Left Seat Propeller Plane*	
	C130J 25000’, 230 KIAS, Balanced	8.17 (x) 3.53 (y) 1.32 (z)
	C130J 25000’, 230 KIAS, Props As-Is	12.2 (x) 4.41 (y) 4.33 (z)
	Right Seat Propeller Plane	
C130J	C130J 25000’, 230 KIAS, Balanced	17.6 (x) 3.33 (y) 3.17 (z)
	C130J 25000’, 230 KIAS, Props As-Is	13.1 (x) 1.14 (y) 1.06 (z)
	Centre Seat Propeller Plane	
	C130J 25000’, 230 KIAS, Balanced	1.84 (x) 0.69 (y) 0.23 (z)
	C130J 25000’, 230 KIAS, Props As-Is	1.63 (x) 1.14 (y) 0.04 (z)
	Left Seat Propeller Plane	
	C130H 25000’, 200 KIAS	6.95 (x) 0.60 (y) 0.84 (z)
C130H (67.5 Hz)	*Right Seat Propeller Plane*	
	C130H 25000’, 200 KIAS C130J	2.59 (x) 0.73 (y) 0.38 (z)
	Centre Seat Propeller Plane	
	C130H 25000’, 200 KIAS C130J	3.34 (x) 1.00 (y) 0.13 (z)

4.2 Summary: C-130J Vibration Environment

The vibration environment in the C-130J is characterised by peaks in the 16-Hz and 100-Hz one-third octave frequency bands, associated with the propeller shaft speed (17 Hz) and blade pass frequency (102 Hz) – with the 102-Hz frequency shown to be the dominant component of the C-130J vibration environment. The highest vibration levels are experienced during high level cruise, and are located principally in the vicinity of the propeller plane, particularly at the outer port and starboard passenger seats. As you move forward and aft of the propeller plane, vibration levels diminish, although the levels are still significant six seats either side of this plane. The level of vibration at the centreline passenger seats is considerably lower (vibration appears to be primarily due to direct transmission of sidewall vibration to the seat via the attachment mechanism). The **high vibration zone** (HVZ) is therefore defined as the outer port and starboard passenger seats located near tie-down positions 6 through to 17. The HVZ is an extrapolation from the findings of the RAF study together with measures from the RAAF study.

The current Australian Standard (AS 2670.1 –2001; based on ISO 2631-1:1997) provides guidance on acceptable levels of human exposure to WBV, and information on the possible effects of vibration on health, comfort and perception. The standard explicitly states that its guidance only applies to WBV within the frequency range 0.1-Hz to 80-Hz. Applying the basic evaluation method recommended in AS 2670, using weighted root-mean-square acceleration measurements within this frequency range, the vibration levels recorded in the C-130J-30 fall below the health guidance caution zones for daily exposure, and therefore could be deemed acceptable (see Table 4). Values were calculated for the Co-Pilot's seat and a passenger seat in the plane of the propeller arc in the cargo compartment for data collected in the second US Air Force study (Smith, 2002b). The weighted acceleration levels were also less than 0.315 m/s^2 rms, which, according to AS 2670, is considered "not uncomfortable" for public transport. However, AS 2670 does not address the peak frequency band (100-Hz) that characterises the C-130J-30 vibration environment.

Table 4 Frequency weighted acceleration and vibration total values for health and comfort based on ISO 2631-1(1997).

Measurement Conditions	Frequency Weighted Acceleration (ms^{-2} rms)	Vibration Total Value
C-130J Co-Pilot Seat 24000′, 220 KIAS, Props Balanced	0.01 (x) 0.02 (y) 0.06 (z)	0.07 (health) 0.07 (comfort)
C-130J Passenger Left Seat 24000′, 220 KIAS, Props Balanced	0.12 (x) 0.04 (y) 0.16 (z)	0.23 (health) 0.19 (comfort)

You would require a vibration total value above 0.25, with 24 hours exposure, to fall within the health caution zone (caution with respect to potential health risks is indicated).

The vibration environment of the C-130H differs from that of the C-130J-30 primarily in terms of the peak frequency band associated with the blade-pass frequency (100-Hz in the C-130J-30; 68-Hz in the C-130H). The acceleration associated with this peak frequency in the C-130J-30 is three times higher than that associated with the peak frequency of the C-130H in the HVZ. It is most likely that it is the experience of this frequency that underlies the subjective reports of increased vibration levels in the C-130J, although these subjective reports are also likely to be influenced by the higher noise levels in the same locations (3-5 dB higher in the C-130J-30). Noise is thought to have considerable influence on how vibration is judged by those exposed, and in turn, vibration will influence judgements of noise (Griffin, 1990). In some conditions it is believed that noise may serve to mask the severity of vibration, while in other conditions noise may result in more unfavourable judgements about vibration levels and comfort. At this point it is not possible to determine which of these factors is predominant in the C-130J.

4.3 Possible Consequences of Exposure to Vibration in the C-130J

At the outset it is important to note that detailed in-situ studies of the effects of exposure to a specific vibration environment (such as that of the C-130J) are required before definitive conclusions about the consequences of exposure can be made. This section aims

to highlight some of the health and performance effects that could be experienced by the crew and passengers of the C-130J, based on the limited research available on this topic.

As the most prominent vibration in the C-130J has been observed at frequencies of 16 Hz and 100 Hz, it is pertinent to look at what changes in health and performance have been associated with exposure to vibration at these frequencies.

4.3.1 16 Hz Effects

At 16 Hz, appreciable vibration may be transmitted up the spine. There may be body resonances associated with degraded vision, manual control, performance and health. As stated previously, headaches have been observed between 10 and 20 Hz, and the head has been observed as the most uncomfortable body location at 16 Hz. Eyestrain has also been observed around this frequency, and it is believed that visual performance is most impaired between 10 and 25 Hz (problems with display vibration may also occur between 2 to 20 Hz) (Grandjean, 1988; Sanders & McCormick, 1993). Changes in digestive function, such as irritations in the intestines and bladder, might also be expected, although most evidence of such conditions has been obtained from epidemiological studies of drivers (e.g., earth-moving equipment, trucks, tractors) who have been exposed to vibration for long periods over several years (Dupuis & Zerlett, 1986; Grandjean, 1988). Hence, it is not clear whether the shorter, less frequent durations of exposure that C-130J crew and passengers are likely to be exposed to will have any serious impact on digestive function. Effects on speech may occur in the range of about 5 to 20 Hz (vertical vibration), with warbling of speech, however this may not be a major concern given that it is unlikely to result in an noticeable reduction in the intelligibility of speech.

With regard to motor performance, large decrements in tracking have occurred between 4 and 20 Hz, with continued effects following exposure (for 30 minutes). Prolonged motor effects suggest that in cases where the C-130J is used for deployment of troops, soldiers might not be able to carry out their duties at peak level even some time after leaving the aircraft. Alarmingly, there is some evidence that exposure to vibration might result in suppression of some reflex responses. In fact this led Martin et al. (1984) to recommend the avoidance of vehicle vibration in the range of 10 to 30 Hz.

Some effects on short-term memory and learning might also be expected. Mean reaction time, number of errors, and attentional lapses were judged to be higher for short-term memory tasks completed at 16 Hz, when compared to those completed in the absence of vibration. A decrease in rate of learning has also been demonstrated to occur during 16 Hz exposure (Sherwood & Griffin, 1990; 1992). The size of decrements in performance of memory and learning tasks during exposure to vibration (see section 2.2.3) suggest that effects on short-term memory and learning may be of concern in cases where use of such skills is required in the cargo compartment of the C-130J (for example, in medical evacuations). It seems likely that the effects of vibration on short-term memory and learning could make a critical difference in cases where such skills were needed in times of very high workload, where the combined effects of psychological stress and fatigue with vibrational effects would be likely to result in more memory problems and slower learning than would be expected with exposure to vibration alone.

While all of these effects could be considered as potential consequences of exposure, the vibration levels measured on the C-130J for this frequency range, and the likely exposure durations that would be experienced, did not indicate a major cause for concern. However, assessments of motor and cognitive functioning under representative C-130J operational conditions (fatigue, environmental, and high demand task conditions) would be necessary to determine if the effects of vibration are significant.

4.3.2 100 Hz Effects

There is very little information on the effects of exposure to WBV above 80 Hz. Until recently, most exposure to higher frequencies was localised (usually hand-transmitted through tool use). For example, local vibration to the hands between 16 and 1000 Hz has been associated with circulatory, bone, joint, muscle, and nerve injuries. However, it is not possible to indicate any specific problems that may occur based on this information, given that the point of exposure and transmission throughout the body is different. Mohr et al. (1965) conducted one of very few studies on exposure to high frequency WBV, and found that at around 100 Hz, mild nausea, giddiness, subcostal discomfort, cutaneous flushing, and tingling occurred. However this was as a result of exposure to accelerations in excess of 10 m/s^2 – much higher than the accelerations observed in studies of vibration in the C-130J. Hence, it seems likely that such symptoms would not occur, or not be as severe as those observed in Mohr et al.'s study. It is also known that there is a resonance of the lower jaw-skull area between 100 to 200 Hz (O'Brien, 2002), however there is no information linking this resonance with pain or other symptoms in this area.

While there is no clear cut evidence of effects of this kind of vibration environment on **health** from the existing literature, the magnitude of the vibration and the likely length of exposure mean that it is highly unlikely that significant and chronic health effects would be experienced.

In the absence of scientific evidence that the vibration environment of the C-130J-30 has no significant impact on the physical and mental functioning required for military operations, passengers who will be required to undertake **high-risk military operations** immediately upon completion of the flight (e.g., airdrop and combat airland operations) should not be seated in the HVZ for prolonged periods.

While vibration within the C-130J is most prominent at around 16 and 100 Hz, the impact of other frequencies of vibration present may also be of concern. In particular, vibration in the range of 4 to 5 Hz in the z-axis, (possibly due to aircraft buffeting and turbulence) has been observed. While vibration around these frequencies is not always present at high magnitude during flight, there should be some consideration of the effects it may have, given that humans are most sensitive to vibration in the z-axis at 4-8 Hz (Bonney, 1995). Even with brief exposures to such vibration some adverse effects might be expected. For example, pains in the chest and abdomen and changes in respiration (Sanders & McCormick, 1993). While such effects are likely to be mild in low stress situations, in times of high workload, and high stress they have the potential to cause substantial decrements to performance of difficult tasks (such as the work carried out by medical

teams during aeromedical evacuation, or impact on the performance of soldiers or paratroopers in combat operations). Backaches have also been associated with exposure to these lower frequencies of vibration (Grandjean, 1988). More serious back problems are likely to occur following long-term exposure to vibration. However backache (particularly lower back ache) is sometimes experienced during shorter exposures, causing annoyance, and possibly disrupting performance. Backaches are highly associated with poor posture, and examinations of aircraft seating have shown that use of seating that improves posture results in reduced reporting back pain (Beevis & Forshaw, 1985; Braithwaite & Vyrnwy-Jones, 1985; Reader, 1985). While vibration may have some influence on back pain during shorter-term exposure to vibration, it seems likely that improvement of posture will be a more influential action to reduce the incidence of short-term back pain in aircraft. Injury may also be of concern if turbulence is likely to result in vibration at a higher magnitude than has been observed in C-130J investigations discussed here (George (2001) indicated that the aircraft used in the AFFTC study did not exhibit the worst vibration for that type of aircraft for the weather conditions they were likely to encounter). Spinal injuries and skin damage could be expected to occur as a result of serious turbulence (von Gierke et al. 1991).

It is important to note that most studies on the impact of vibration on the human body have examined the effects of vibration on otherwise healthy individuals. Hence, while the C-130J is used as an aeromedical evacuation vehicle, to transport the sick and injured, the effect of vibration on patients is difficult to estimate. Depending on the nature of the illness or injury suffered, vibration might be expected have to have more serious consequences for a patient's health, however, to what extent, and in what situations this might occur is yet to be determined.

4.4 Reducing vibration

Given the concerns raised regarding vibration in the C-130J, it is appropriate to examine what actions might be taken to reduce crew and passenger exposure to vibration in the cargo compartment. A number of options are available for consideration. One very effective method of reducing exposure to vibration would be to simply instruct crew and passengers (particularly MEDEVAC patients) not to sit in areas where vibration levels are highest (or at least to reduce the amount of time spent in these areas). In the case of the C-130J this would mean placing limitations on the time spent in seats in and around the propeller plane. Based on the results of their study of the CMk4 (C-130J-30) and CMk5 (C-130J) Leeks et al. (2002) recommended that "Personnel carried in the rear cabin during high level sorties should spend minimal time in the high vibration areas identified during this study as longer sorties may approach the ISO discomfort and fatigue-decreased proficiency boundaries." (p. 7) Ideally such guidelines should be followed where possible, however, in some cases spatial constraints may prevent crew and passengers from avoiding these high vibration areas. Hence, it is pertinent to look at modifications that may be made to the aircraft (and seating) that might reduce the transmission of vibration to the human body. Dynamic propeller balancing and the employment of optimum synchrophase angles, adjustment of seating materials and attachment of seats, and introduction of vibration-reducing materials into the fuselage will all be considered briefly here.

As discussed earlier it is of upmost importance that the problem frequencies that lead to the most discomfort be identified such that the most appropriate methods, which focus specifically on reduction of those frequencies can be implemented. A major difficulty in selecting methods for reducing exposure to vibration is that certain measures may be taken to reduce transmission of a specific vibration frequency, but also inadvertently increase transmission of other problem frequencies. Hence, ideally, reducing vibration at the source (e.g., through dynamic propeller balancing and optimum synchrophase angles) rather than trying to attenuate it within the cargo compartment may be the most desirable option.

With regard to seating, the use of cushions to reduce seat base vibrations in the C-130J-30 has been investigated (T.D. Higgs, personal communication, June 18, 2001). During high speed cruise conditions participants were required to make comments and give a rating out of 10 (i.e., 1 – least effective, 10 – most effective) of the effectiveness of a variety of different cushion types (as well as a regular uncushioned canvas seat) at reducing transmission of vibration. Cushions evaluated were made out of Sorbothane, sheep fleece, Neoprene, polyurethane foam, and jelly. The subjective ratings indicated that thick jelly cushions were most effective at attenuating vibrations, while typically use of the uncushioned seat resulted in comments of "tingling in lower abdominal body parts and rapid onset of discomfort". It was also noted that there were no problems with slippage when using the thick jelly cushion, and that instalment of 12 of these cushions (in vibration problem areas) would result in an overall weight increase of less than 100 pounds per aircraft, which was "…not considered to be an unreasonable penalty in comparison to the passenger benefits". The same cushioning materials were also assessed in their ability to reduce vibration transmission from the floor. While the thick jelly material was once again considered most effective in attenuation of vibration, three layers of neoprene were considered to result in a similar reduction of vibration transmission, whilst being more stable than jelly. Hence it appears that simply adding an appropriate seat cushion (and floor lining) may go a long way to reduce discomfort due to vibration. Further investigation of the worth of modifications to seating might include examination of the effects of providing cushioning to the seat back, and examination of methods of reducing transmission of vibration from the sidewall of the aircraft to the seats that are attached to it. Calculation of SEAT values (see section 3.1) in future investigations might also be useful, particularly in clarifying that the subjective assessments given are related to attenuation of vibration rather than other aspects of comfort not related to vibration.

5. Conclusions and Recommendations

Vibration is an extremely complicated phenomenon, and human exposure is difficult to investigate in a comprehensive fashion. Although some broad guidelines (based on the ISO 2631 standard) may be applied to give an idea of the vibration dose to which people may safely be exposed, there is no easy way of predicting the precise changes that will occur during and after an individual's exposure.

As an initial step in the process of determining how vibration will influence those exposed it is appropriate to determine the vibration characteristics of the environment and find changes in human health, performance, and comfort that have been associated with these characteristics. This may be a helpful early indicator of the changes that may occur. It is essential to consider both the duration and magnitude of exposure (for example, serious health problems may not be an issue for those who undergo only brief exposure to the vibration environment).

In the case of the C-130J (the C-130J-30 in Australia), crew have reported high levels of vibration that they believe are annoying and fatigue-promoting. Studies of exposure to vibration in the C-130J to date have indicated that the high vibration zone (HVZ) is located in the cargo compartment, more particularly in locations near the propeller plane. Given the results of the studies described above, and with an understanding of the limitations imposed by the unique vibration environment of the C-130J-30, the following recommendations are made:

6. The vibration levels measured on the **flight deck** of the C-130J are unlikely to result in either short-term or long-term deleterious effects on the health and functioning of aircrew.
7. While the precise impact of 100 Hz vibrations on aircrew and passengers is uncertain, the magnitude of the vibration and the likely length of exposure mean that it is highly unlikely that significant and chronic health effects would be experienced. This conclusion holds for passengers with normal levels of health. The impact of the higher levels of vibration in the propeller plane on patients being transported as part of aeromedical evacuation missions is unknown, and likely to depend on the nature of their illness/incapacitation and on their means of carriage. Until definitive advice/studies are produced to clear the HVZ of the aircraft of health risk to such patients, it is recommended that such passengers are not transported in the HVZ of the aircraft. Display jitter levels measured at the Aerial Weather Reconnaissance Officer (ARWO) station of a WC-130J were within MIL-STD-1472 limits (George, 2001), and there were no reports of visual blurring, so it is presumed that displays associated with medical equipment in a medivac missions could be used effectively in the HVZ of the cargo compartment.
8. There is evidence that vibration can have negative effects on human performance through the impact of increased fatigue and reduced levels of attention. This evidence does not extend to vibration frequencies greater than 80Hz, although there have been subjective reports of increased fatigue and irritation in the C-130J linked to the vibration/noise environment. It is recommended that in the absence of scientific evidence that the vibration environment of the C-130J-30 has no significant impact on the physical and mental functioning required for military operations, that passengers who will be required to undertake high risk military operations immediately upon completion of the flight (e.g., airdrop and combat airland operations) should not be seated in the HVZ for prolonged periods. Passengers who will not be required to undertake high risk military operations could be accommodated in the outer port and starboard passenger seats in the HVZ, but it is recommended that they be informed of potential fatiguing effects of

the zone, and be advised to spend time away from the zone when safe and practical.

9. It is recommended that laboratory or in situ studies be carried out to determine the effect of the C-130J vibration environment on human performance, the duration of any of these effects, and to validate the extent of the proposed HVZ.

10. Along with prominent vibration, many military aircraft are characteristically very noisy during flight, and it is known that noise will influence perception of vibration. A further recommendation will be that in researching the impact of vibration in the C-130J-30, interactions with other characteristics of the flight environment - in particular acoustic noise, should be closely examined. It's possible that in reducing noise, crew and passengers might find the vibration less uncomfortable, and therefore more tolerable. However, it would be wise to exercise caution in adjusting the relationship between noise and vibration, given that at certain volumes noise may actually serve to mask the severity of vibration.

11. On the assumption that the accommodation of passengers in the HVZ is necessary for optimising military objectives it is recommended that strategies to reduce the vibration transmitted to passengers seated in this zone be explored. These strategies range from reducing the level of blade pass frequency vibration through optimisation of synchrophase angles, to the isolation of passenger seating through more effective mounting of the seats to the sidewall, to the use of seat cushions/padding. In all of these cases it would be necessary to measure vibration levels at the seat pan following the application of any of these strategies. A critical issue is determining an appropriate target level of vibration to achieve. As the flight deck vibration levels have been deemed acceptable, they could be considered an appropriate target.

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19. ABSTRACT

Human exposure to whole-body vibration (WBV) has been associated with a variety of changes in health, comfort, and occupational functioning. In the C-130J Hercules aircraft, crews from both Australia and overseas have reported that the vibration in the cargo compartment of the aircraft exceeds previous levels and that it is both annoying and fatigue-promoting. This report examines the issue of human vibration in the C-130J, providing an overview of the characteristics of vibration and human exposure to vibration, as well as a review of studies that have measured the vibration levels in the C-130J. The likely consequences of exposure to vibration in the aircraft are discussed and recommendations for managing the issue are provided.

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